Development of Psychrometric diagram for the energy efficiency of Air Handling Units

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ABSTRACT

Air Handling Unit (AHU), as a system for space heating and cooling is one of the most relevant causes of energy consumption in both residential and tertiary sector buildings. As the energy efficiency of AHU is closely linked to the climate conditions, a special attention should be given about varying yearly climate conditions in different geographical locations. This paper presents an approach for calculating the energy efficiency by using the Psychrometric diagram which has been divided into five zones based on different functions of AHU; for each zone outside climatic has a particular status with yearly weight that is corresponds for specific AHU's operation. To achieve this, different combination of outdoor climatic parameters (Dry and wet bulb temperature and humidity ratio) has been considered as varieties for defining zones. Sum of AHU's energy consumption in different zones based on related weighting factor will result in the total annual consumption of energy.

KEYWORDS

Air Handling Units (AHU), Energy efficiency, Psychrometric diagram

1 INTRODUCTION

The residential buildings represent about 40% - 50% of the total energy consumption and the major part of this consumption is used for Air Handling Units (AHU) to prepare the thermal comfort (Council 2013). The amount of required energy depends on outdoor condition fluctuations, interaction between natural gravity and air tightness of the building, heat exchangers, efficiency of other equipment, and operation modes of AHU systems (Misevičiūtė et al. 2017). Fans, heat exchangers and heaters as the main elements that use energy in AHU, have a significant effect on both energy needs of a building and the energy efficiency of a system. AHU's energy consumption can be calculated in two ways. In the case of working air handling units the actual consumption data can be exactly determined by measurement. But according to Directive 2002/91/EC (Union 2009) on the energy performance of buildings (EPBD) it is also important to determine the expected energy consumption in the designing phase. However, the calculation of the energy consumption of air handling units is still problematic, especially when the climate condition differs.

The energy efficiency of AHU system is closely linked to geographical location (Trojanova et al. 2009), especially to the outdoor climatic parameters such as dry bulb temperature, wet bulb temperature, relative humidity and enthalpy. But, there is too little attention paid to the evaluation of the exact climate that is the core in AHU application and related energy analysis. Therefore, there is a need to investigate methods that are being used to climatic parameters in relation to AHU operation. This paper aims at demonstrating the application of the different climatic parameters for the evaluation AHU's energy consumption. Special attention is given to the proposition of Psychrometric diagram for AHU based on different operations and calculating the yearly energy efficiency based on it.

2 PSYCHROMETRIC DIAGRAM

An important pioneer of thermal comfort representations was Victor Olgyay, who introduced the "Bioclimatic Chart" (Olgyay, 1963). However, the thermal comfort area reported in his chart was not consistent with ASHRAE 55 thermal comfort areas. Givoni, partially converted the Olgyay's representation to the psychrometric chart (Figure 1) and added rules about passive heating and cooling strategies (Givoni, 1969).

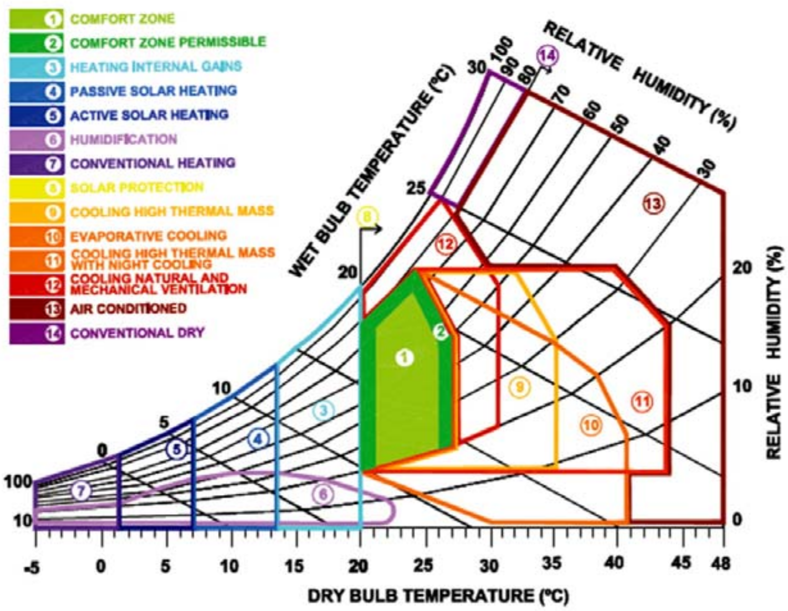

Figure 1. Psychrometric chart (Givoni 1992)

The application of Givoni's psychrometric chart in energy efficiency of air conditioning is studied in some studies. Zhang and Niu studied the applicability of heat and moisture recovery systems in Hong Kong by classifying the psychometric chart into six regions based on outdoor temperature and humidity (Zhang and Niu 2001). Mohammad Rasouli, proposed different scenarios for Energy Recovery Ventilators (ERV)'s function, whether it should be operated or stopped depends on several factors such as, the indoor and outdoor conditions by dividing the psychrometric chart into sub-regions that establish the conditions when the ERV needs to be controlled (Rasouli, Simonson, and Besant 2010). In other study, Stefano Schiavon presented a new web application (Schiavon, Hoyt, and Piccioli 2014) for thermal comfort visualization and calculation according to ASHRAE Standard 55-2013 (ASHRAE 2013). Simonson et al. experimentally validated two strategies to control energy wheels by applying an operating condition factor which presented the ratio of latent to sensible energy potential of inlet airstreams (Simonson and Besant 1999). Since use of this methodology is investigated for the operational efficiency of air conditioning systems and buildings energy efficiency, the use of this chart could also be useful in energy efficiency calculation of AHU.

3 AHU ENERGY EFFICIENCY

The treatment of the air in AHU requires different types of energy, depending on the utilized systems and components which causes specific operation (Eurovent, 2005):

Heating: By means of thermal energy (heat exchangers fed with hot water) or by means of electrical energy (electrical heat exchangers). In addition electrical energy is demanded to run the utilized pumps.
Cooling: By means of cooling systems based on compression cycles using electrical energy for running the system, or based on absorption cycles using thermal energy for operating the absorption cycle process or based on evaporation processes like adiabatic cooling. In addition electrical energy is demanded to run the utilized pumps.
Humidification: By water (evaporation humidification) or vapor (steam humidification). In case of steam humidification, thermal energy is required for the generation of the steam. In case of evaporation humidification, electrical energy is demanded to run the injection pumps. Evaporation heat is withdrawn from the passing air (thermal energy)
Dehumidification: The delivery air stream after passing the heat or humidity recovery unit is cooled in the cooling coil to the dew point temperature and then the additional cooling power for dehumidification is calculated.
Ventilation: In AHU air is transported by means of fans, using electrical energy.
Auxiliary devices: To operate AHU properly, a number of auxiliary devices such as damper motors, control equipment, lighting systems and pumps are needed. All of these devices require electrical energy.
Therefore, the overall demand of energy for AHU can be summarized into two classes of electrical energy and thermal energy. A realistic indication of energy efficiency over an entire year can be achieved by using Coefficient of Performance (COP) which indicates on how efficient AHU operates over an entire cooling or heating season (Ertesvåg 2011). A ratio of the thermal capacity is in watts and the electricity input values is in watts.

$$COP = \frac{Q}{\mathrm{P}} \tag{1}$$

Where;

Q = Useful heat supplied or removed by the considered system (W).
P = Work (electricity) required by the considered system (W).

The COP is therefore a measurement of efficiency; the higher the number, the more efficient the system is. The COP is dimensionless because the input power and output power are measured in Watt. The COP is also an instantaneous measurement in that the units are power which can be measured at one point in time.

3.1 Electrical energy calculation

In our calculation, we only consider the fan's electrical consumption. The absorbed power supplied from the mains to each individual fan can be expressed as follows ((EU) No 327/2011):

$$P_{el} = q_V . \Delta p_{\ fan} / \eta_e . 1000 \tag{2}$$

Where;

P_{el} = Absorbed electrical power supplied from the mains (W)
q_V = Air volume flow through the fan (m3/s)
Δp_{fan} = Total pressure rise from the fan inlet to the outlet (Pa)
P_{shaft} = Mechanical power supplied to the fan shaft (W)
η_e = Overall efficiency of the fan and motor system = η_{shaft} x η_{tr} x η_m x η_{aceq}

All values are applicable to an air density of $\rho air = 1.2$ kg/m3

3.2 Thermal energy calculation

The thermal energy consumption of a sensible heating/cooling coil and heat exchanger is calculated with the equation (Eurovent, 2005):

$$Q_s = q_v.\rho.c_p.\,(t_{out} - t_{in}) \tag{3}$$

Where;

Q_s = Sensible energy consumption
q_v = Air flow rate in m3/s
ρ = Density of the considered air flow rate in kg/m3 = 1.2 kg/m3
c_p = Specific heat of the air in kJ/kg.k = 1.00 kJ/(kg·K)
t_{out} = Temperature of the air leaving the coil in C°
t_{in} = Temperature of the air entering the coil in C°

The momentary thermal energy consumption for sensible cooling/heating of air when the moisture of air changing is calculated with the equation:

$$Q_s = q_v.\rho.\,(h_{in} - h_{out}) \tag{4}$$

Where;

Q_s = Sensible energy consumption when the moisture of air changing
q_v = air flow rate in m3/s
ρ = density of the considered air flow rate in kg/m3 = 1.2 kg/m3
h_{in} = enthalpy of the air at the inlet of the coil in kJ/kg
h_{out} = enthalpy of the air at the outlet of the coil in kJ/kg

The momentary energy consumption for latent heating/cooling coil and heat exchanger (dehumidification/humidification of air in a cooling coil) is established with the formula (Eurovent, 2005):

$$Q_l = q_v.\rho.\,(x_{in} - x_{out}).\,2500 \tag{5}$$

Where;

Q_l = Latent energy consumption
q_v = Air flow rate in m3/s
ρ = Density of the considered air flow rate in kg/m3 = 1.2 kg/m3
x_{in} = Moisture content of the air at the inlet of the coil in kg/kg
x_{out} = Moisture content of the air at the outlet of the coil in kg/kg
2500 = Condensation (evaporation) heat of water vapor at moderate coil outlet temperatures in kJ/kg

Total thermal energy (Q_t) consumption of a cooling/heating coil is the sum of the energy consumption for sensible and latent cooling/heating (Eurovent, 2005). Hence:

$$Q_t = Q_l + Q_s \tag{6}$$

4 METHODOLOGY

The distribution functions of outdoor air parameters can be applied for determine the actual energy consumption of AHU (Kajtár and Vörös 2007). Temperature is commonly used as the thermal comfort control objective in early HVAC systems. But, temperature alone does not ensure a person's thermal comfort (Kajtár and Kassai 2010). From the perspective of air conditioning technology the climatic parameters of outdoor air (Dry bulb temperature, Wet bulb temperature, humidity ratio, relative humidity and enthalpy) that vary in daily and season period (Kazuhiro 2005.), could couple with each other for effective planning and operation. However, it is difficult to control factors when each has its own strict set point.
An air handling unit contains two main groups of elements: supply and exhaust units. The main parts of these groups are including filter, heat recovery unit, cooling and heating coils, by-pass, adiabatic humidifier and fans, which based on different climatic conditions could conclude different operations; ventilation, cooling, cooling and humidification, cooling and dehumidification, heating and heating and humidification. Calculations of these parameters are really complicated by variable efficiency operation of air handling units due to fluctuation of outdoor condition (Kajtár and Kassai 2010). Therefore, calculating the energy efficiency based on different scenarios regarding the operational conditions of AHU could simplifier the process. These different scenarios are presented by dividing the psychrometric chart into five sub-zones (Figure 2).

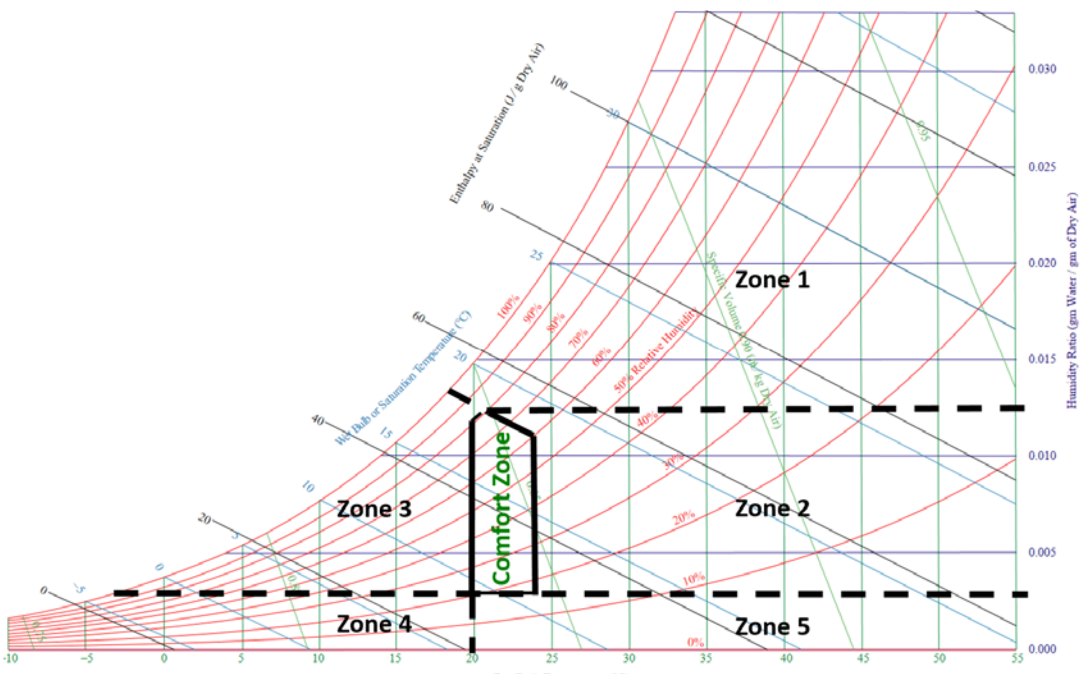

Figure 2. Climatic zones based on AHU's function

By selecting the summer indoor comfort condition as a reference condition (Comfort Zone, Figure 2), the psychrometric chart can be divided into five areas based on the temperature and humidity ratio. For thermal energy calculation, the center of comfort zone (Dry bulb temperature 22°c and 50% relative humidity) is selected as a reference indoor condition. The area with higher outdoor temperature and humidity ratio than the comfort zone (Zone 1) corresponds to yearly horses that AHU should operate as cooling and dehumidification, the area with higher temperature and same humidity ratio (Zone 2) that needs cooling and the area with higher temperature and less humidity ratio (Zone 5) that should be cooled and humidified.

Furthermore, the area with lower outdoor temperatures than the comfort zone can be also divided into two zones: heating (Zone 3), heating and humidification (Zone 4).

$$\text{GCOP} = \sum_{i=1}^{6} COPi\ Wi \quad (7)$$

Where;

GCOP = Geographical Coefficient of Performance
$COPi$ = COP of each zones
Wi = Weight of each zone

Therefore, based on the function of AHU in each zones, COP, could differ. Multiplying COP of each zone with weight of hourly data over an entire year results Geographical COP (Equation 7) that is a new way of measuring the true energy efficiency of AHU. This new measure gives a more realistic indication of the energy efficiency and environmental impact of a system.

4.1 Energy efficiency calculation

Zone 1; Cooling – Dehumidification (Humidity ratio ≥ 13 [g/kg], Wet Bulb ≥ 18.5 °C)
When air is cooled below the dew point temperature, condensation occurs and moisture is removed from the air stream. The exiting air stream is at a lower temperature and humidity ratio than the incoming air stream. The cooling to condense water from the air is called latent cooling or dehumidification. Thus, the movement of a dot from this zone to comfort zone includes both sensible and latent cooling.

$$COP_{Z1} = [(Q_{CC} + Q_{DHU} + Q_{HRS}) / P_{el}].\ W_1 = [(Eq.3 + Eq.5 + Eq.4)/ Eq.2].W_1 \quad (8)$$

Where;

Q_{CC} = Cooling coil thermal energy
Q_{DH} = Dehumidification thermal energy

4.2 Zone 2; Cooling (Humidity ratio < 13 [g/kg], Humidity ratio ≥ 3 [g/kg], Dry Bulb ≥ 24°C)

On a psychrometric chart, the exiting air is at a lower temperature than the incoming air while the humidity ratio remains constant since no moisture is condensed from the air. Reducing the temperature of air without changing the quantity of water in the air is called sensible cooling. The movement of a dot from this zone to comfort zone is possible by sensible cooling.

$$COP_{Z2} = [(Q_{CC} + Q_{HRS}) / P_{el}].\ W_2 = [(Eq.3 + Eq.4) / Eq.2].W_2 \quad (9)$$

4.3 Zone 3; Heating (Humidity ratio ≤ 13 [g/kg], Humidity ratio ≥ 3 [g/kg], Dry Bulb < 20°C)

In HVAC systems, air is typically heated by passing it over a heating coil or use of electrical strip heaters. A schematic of a cooling coil is shown below. Since the humidity ratio remains unchanged, and so we use a horizontal line on the psychrometric chart to represent this process. Heating will result in lower relative humidity.

$$COP_{Z3} = [(Q_{HC} + Q_{HRS}) / (P_{el} + P_{Aux.})].W_3 = [(Eq.3 + Eq.4) / (Eq.2+ P_{Aux.})].W_3 \quad (9)$$

Where;

P_{Aux} = Electrical energy consumption for heating coil (In case of using electrical heater)

4.4 Zone 4; Heating – Humidification (Humidity ratio < 3 [g/kg], Dry Bulb < 20°C)

Heating and Humidifying is the process of simultaneously increasing both the dry-bulb temperature and humidity ratio of the air. The total heat gained (Q) in going from the initial to the final condition can be broken into sensible and latent heat portions. The humidity ratio is constant for the horizontal movement (sensible) and the dry-bulb temperature is constant for the vertical movement (latent). Humidification process is done by humidifiers that can be classified to; steam or water and/or depending on the principle of operation. For heating, in case of using electricity, P_{Aux} adds to electrical energy calculation.

$$\begin{aligned} COP_{Z4} &= [(Q_{HC} + Q_{HU}+ Q_{HRS}) / (P_{el} + P_{Aux.})].W_4 \\ &= [(Eq.3 + Eq.5 + Eq.4)) / (Eq.2 + P_{Aux.})].W_4 \end{aligned} \quad (10)$$

Q_{HU} = Humidification thermal energy
P_{Aux} = Electrical energy consumption for humidification (In case of using electrical steamer)

4.5 Zone 5; Cooling – Humidification (Humidity ratio < 3 [g/kg], Dry Bulb ≥ 20°C)

Cooling and Humidifying is the process of decreasing the dry-bulb temperature and increasing humidity ratio of the air. The total heat gained (Q) in going from the initial to the final condition can be broken into sensible and latent cooling portions.

$$\begin{aligned} COP_{Z5} &= [(Q_{CC} + Q_{HU}+ Q_{HRS}) / (Eq.2 + P_{Aux.})].W_5 \\ &= [(Eq.3 + Eq.5 + Eq.4)) / (Eq.2 + P_{Aux.})].W_5 \end{aligned} \quad (11)$$

Calculation of COP for each zone and sum of them together conclude a specific SCOP for each geographical location, which is a base for AHU's energy efficiency. The much specific AHU's COP closer to GCOP, the more it is efficient. Case study by analyzing five different geographical location is proposed in the next section to present the concept in real case.

5 CASE STUDY

For plotting the hourly climatic data during a year for each geographical location, there are three tools that perform thermal comfort calculations, two of which are also able to visualize comfort conditions: Climate Consultant (Milne 2016), Autodesk Ecotect Weather Tool and the ASHRAE Thermal Comfort Tool. In this paper, Climate Consultant is chosen that is an excellent graphics-based, free, stand-alone computer program that helps users understand weather data used for building performance software. The program reads a weather file and presents a summary of the weather data as an overview of the selected climate, where each dot represents the temperature and humidity for each hour of the year. It uses standardized weather data for energy simulation software. To have a diverse climatic situation, Copenhagen, Athens, New Delhi and Riyadh are chosen for GCOP calculation.

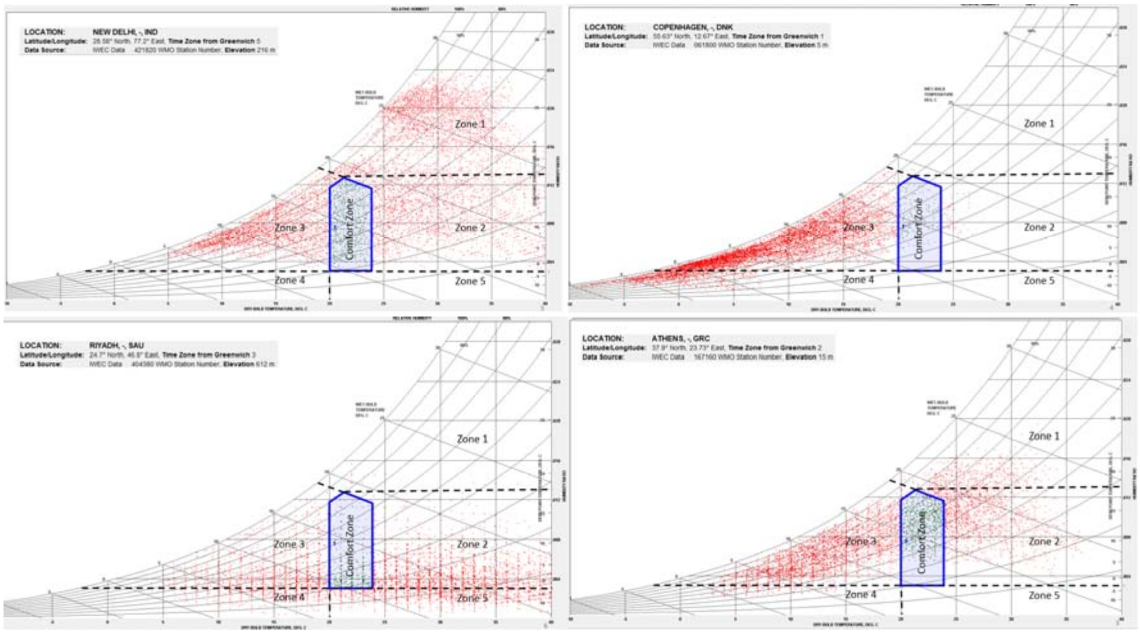

Figure 3. Psychrometric chart with zones based on AHU's function

The yearly climatic data for each city is extracted from Energy Plus website and imported to Climate Consultant 6.0 software to illustrate the data on psychrometric chart. Based on yearly data for each city, the percentage of hourly spots for each zone is calculated and presented in table below.

Table 1: Zone weights for different cities

CITY	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5	COMFORT ZONE
RIYADH	0.23%	40.49%	21.93%	7.15%	22.00%	8.22%
NEW DELHI	36.69%	23.32%	29.43%	0%	0.16%	10.41%
ATHENS	6.27%	19.52%	57.52%	1.83%	0%	14.87%
COPENHAGEN	0.13%	0.58%	85.52%	11.12%	0%	2.66%

The next step of methodology is to calculate the COP of each zones for each city, in order to find the GCOP for AHU. Due to the limits of pages for submission process, we have chosen one city (Riyadh) to show the rest of calculation. A certified AHU with energy grade A+, which is certified by Eurovent Certita Certification is chosen as the case. The data related with thermal energy calculation and electrical energy consumptions are obtained from performance calculation software. The software calculates in and out air temperature, temperature ratio, pressure drops, the fans capacity and electrical consumption and electrical consumptions of other devises. We conclude the example by calculating the COP_i, using the above equations, summarized in Table 2. The supply and exhaust airflows are assumed 9000 m^3/h.

Table 2: Output of software and calculation results based on above equations

Symbol	Value
$Q_{CC} = Q_S$	31 kw
$Q_{HC} = Q_S$	28 kw
$Q_{HRS} = Q_{S\ (Moisture\ change)}$ - Summer	63 kw
$Q_{HRS} = Q_{S\ (Moisture\ change)}$ - Winter	20 kw
$Q_{HU} = Q_l$	44 kw
$Q_{DHU} = Q_l$	20 kw
P_{el}	3 kw

$P_{Humidification}$	6 kw
COP_{Z1}	(31+20+63)/3 = 38
COP_{Z2}	(31+63)/3 = 31.33
COP_{Z3}	(28+20)/3 = 16
COP_{Z4}	(28+44+20)/ (3+6) = 10.22
COP_{Z5}	(31+44+63)/ (3+6) = 15.33

$$GCOP = 38*0.23\% + 31.33*40.49\% + 16*21.93\% + 10.22*7.15\% + 15.33*22\% = 0.088 + 12.68 + 3.51 + 0.73 + 3.37 = 20.38$$

This amount of GCOP with some tolerances could be a reference number for energy efficiency of AHU that are going to use in Riyadh and other cities with similar climatic condition.

6 CONCLUSIONS

The result of dividing yearly energy consumption of AHU based on different operations for climatic zones, was studied in this paper. The objective was to propose a methodology for both warm and cold climates with different humidity rates. This methodology results a number which could be used as an index for energy efficiency of AHU is different climatic situations.
Due to de complexity of AHU's function and climatic parameters, the methodology needs improvements in terms of zones definition, AHU criteria such as unbalanced are flows and different case design and including wet bulb temperature in some equations. This study will continue with promoting zones, in order to have precise simulation for function of AHU. Moreover, a performance factor will add to GCOP formula to include different functional parameters in future studies.

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